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Abstract. *Reduction of ammonia emissions from animal feeding operations is important from the perspective of environmental policy and its impact on agriculture. A laboratory study was conducted to evaluate how rate and frequency of urease inhibitor application affect ammonia emissions from simulated beef cattle feedyard manure surfaces. The urease inhibitor N−(n−butyl)thiophosphoric triamide (NBPT) was applied at rates of 0, 1, and 2 kg ha^{-1}, at 8, 16, and 32 day frequencies, and with or without simulated rainfall. Synthetic urine was added every two days to the manure surface. Gaseous ammonia was trapped by bubbling through a sulfuric acid solution using a vacuum system and analyzed for nitrogen using automated procedures. NBPT applied every 8 days was most effective, with the 1 and 2 kg NBPT ha^{-1} treatments resulting in 49% to 69% reduction in ammonia emission rates, respectively. The 8−day, 1 kg NBPT ha^{-1} treatments had the most promising benefit/cost ratios of 0.48 to 0.60. Simulated rainfall reduced the ammonia emission rates from 1% to 25% as compared to the non−rainfall treatments, although the differences were not statistically different. The use of NBPT for reducing ammonia emissions looks promising; however, possible buildup of urea in the pen surface may require a higher NBPT application rate with time.*

Keywords. *Air quality, Ammonia, Beef cattle, Feedlot, Manure, Nitrogen, Odor, Urea, Urease.*

Cattle production is the principal animal agricultural operation in the Texas Panhandle area, with more than seven million beef cattle fed each year (SPS, 1999). There are at least 70 feedyards in the area with capacities greater than 20,000 head (Parker et al., 1997). Large amounts of manure are produced from these feedyards. The manure is rich in nutrients and is used as fertilizer in crop production. However, large amounts of manure left in the feedyard pens can contribute to water and air pollution if not managed properly.

In open−lot beef cattle feedyards, manure is left in the pen for 120 to 360 days (Parker et al., 1997). During this time, significant amounts of nitrogen can be volatilized from urine and feces on the feedyard surface. Scientists have estimated that as much as 50% of feed N is lost via volatilization (Bierman et al., 1999). Nitrogen loss into the atmosphere results in higher C/N and lower N/P ratios in the manure, which leads to less desirable fertilizer value, and contributes to air quality concerns. The need to decrease emissions of ammonia (NH_3) and other gases produced by livestock and their waste products has grown in recent years. As a result of data indicating that these gases have the potential to contribute to the greenhouse effect, acid rain, and/or stratospheric ozone depletion, many European countries currently have regulations limiting NH_3 emissions from concentrated animal feeding operations. Moreover, emissions of NH_3 and oxides of N and S have been implicated as potential contributors to fugitive dust emissions, especially PM−10 and PM−2.5 particulates (Morse, 1996a, 1996b).

The abatement of NH_3 emissions is necessary due to several environmental, agricultural, social, and economic reasons. Intensive livestock operations can be a significant source of NH_3 emissions to the atmosphere. Although some of the NH_3 emitted will be deposited locally, it can also be deposited thousands of kilometers away, contributing to trans−boundary air pollution across countries (UNECE, 2001). These emissions may impact the surrounding ecosystem and their use (Arogo et al., 2001). Ammonia emissions are given importance all over the world. Studies in Europe have shown that measures to reduce NH_3 generally reduce odors as well (Xue et al., 1998). Decreasing NH_3 emissions can not only decrease environmental impacts, but also can increase the fertilizer value of the manure.

Several chemical amendments and additives have been studied to reduce NH_3 emissions (Shi et al., 2001; Cole et al., 1999; Miner and Stroh, 1976). Additives rely on several modes of action. Earlier research has shown that soil pH affects losses of NH_3 from cropped fields, with high pH resulting in greater NH_3 losses (Harmsen and Kolenbrander, 1965). Chemical amendments such as alum ($Al_2(SO_4)_3$) and calcium chloride reduce NH_3 emissions by decreasing pH and through cation exchange (Shi et al., 2001). Hydrolysis of

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the Al^{3+} ion in alum frees three H^+ ions, decreasing pH and reducing NH_3 emissions. Through cation exchange, hydrogen ions are released and replaced by aluminum or calcium ions, again resulting in decreased pH and reduced NH_3 emissions.

Kithome et al. (1999) evaluated the efficacy of the chemical amendments $CaCl_2$, $CaSO_4$, $MgCl_2$, $MgSO_4$, and alum for reducing NH_3 emissions from composted poultry manure. Mixing 20% $CaCl_2$ or $MgCl_2$ with compost reduced NH_3 emissions to 10% to 20% of the control, whereas 20% alum reduced NH_3 emissions to 74% of the control. However, $CaSO_4$ and $MgSO_4$ ineffectively reduced NH_3 emissions. Moore et al. (1995) and DeLaune et al. (2004) reported that alum significantly reduced NH_3 volatilization from poultry manure. Lowering the pH by direct addition of sulfuric acid to cow and pig slurries has been shown to reduce NH_3 volatilization (Stevens et al., 1989).

Compounds that inhibit the enzymatic breakdown of nitrogenous compounds present in feces and urine can also decrease NH_3 production. Much of the nitrogen excreted in the urine is in the form of urea ($CO(NH_2)_2$), which is rapidly hydrolyzed to ammonium and eventually to NH_3 gas by the urease enzyme produced by soil and fecal microbes. Urease inhibitors can block the hydrolysis of urea to ammonium (Varel, 1997; Varel et al., 1999) and thereby decrease NH_3 production.

Nitrogen can be conserved and nitrogen and NH_3 emissions decreased by altering the carbon/nitrogen ratio. Subair et al. (1999) evaluated the ability of paper products added to liquid hog manure to reduce NH_3 emissions, and found that NH_3 volatilization was reduced from 29% to 47% by increasing the C/N ratio of the liquid hog manure.

In addition to chemical and enzymatic amendments, several commercial products are now marketed for reducing NH_3 emissions. Zhu et al. (1997) evaluated several commercial additives for reducing NH_3 emissions from swine lagoons and found that NH_3 emissions ranged from 64% to 137% of the control.

Shi et al. (2001) evaluated several amendments for reducing NH_3 emissions from beef cattle manure under laboratory conditions. Several amendments showed promise in reducing NH_3 emissions, including alum (NH_3 emissions of 2% to 8% of the control), calcium chloride (21% to 29% of the control), humate (32% to 40% of the control), and the urease inhibitor N−(n−butyl)thiophosphoric triamide (NBPT) (34% to 35% of the control). NBPT was the only amendment that had a benefit/cost ratio greater than 1.0.

The purpose of this research was to continue the work of Shi et al. (2001) and further investigate the ability of the urease inhibitor NBPT to reduce NH_3 emissions from simulated beef cattle feedyard surfaces under a variety of simulated field conditions.

Table 1. Treatments used in the experiment.

Treatment	NBPT Application: Rate (kg ha^{-1})	NBPT Application: Frequency (days)	Simulated Rainfall[a]
1	Blank[b]	None	No
2	Control[c]	None	No
3	1	8	No
4	1	8	Yes
5	1	16	No
6	1	16	Yes
7	1	32	No
8	1	32	Yes
9	2	8	No
10	2	8	Yes
11	2	16	No
12	2	16	Yes
13	2	32	No
14	2	32	Yes

[a] Treatments with simulated rainfall received 0.6 cm water every four days.
[b] No soil/manure.
[c] Soil/manure only.

OBJECTIVES

The specific objectives of this research were to:

- Determine how often NBPT should be applied to minimize NH_3 emissions in simulated feedyard conditions.
- Determine how precipitation affects the effectiveness of NBPT.
- Estimate the economic effectiveness of using NBPT.

MATERIALS AND METHODS

EXPERIMENTAL DESIGN

The experimental design included the following three factors, which were chosen based on findings of Shi et al. (2001):

- NBPT application rate (1 or 2 kg ha^{-1}).
- NBPT application frequency (applied every 8, 16, or 32 days).
- Simulated rainfall (no water added or 0.6 cm water added every four days).

The design consisted of 14 treatments, including 12 treatments resulting from combinations of the three factors and an additional two treatments consisting of a blank (no soil/manure) and a control (table 1). There were three replications per treatment for a total of 42 experimental units.

EMISSION APPARATUS

The emission apparatus consisted of air emission chambers constructed of Tupperware (16.7 × 16.7 × 17 cm deep) (figs. 1 and 2). Each chamber was connected to an NH_3 collection trap containing 100 mL of 0.9 M sulfuric acid. Each acid trap was connected with equal lengths of plastic tubing to a common plastic container to ensure an equal airflow from all the chambers (figs. 1 and 2). The common container was connected to a vacuum pump (model 80M48S17D1180JP, Marathon Electric, Wausau, Wisc.). The ambient air above the manure was pulled through the acid traps by the vacuum pump. The total airflow was adjusted to obtain a flow rate of 1.4 L min^{-1} in each chamber. Flow rates were measured using a glass rotameter with a stainless steel float (model FL−105, Omega Engineering, Inc., Stamford, Conn.). Acid traps were changed every 48 h. Acid samples were analyzed for total nitrogen by automated procedures using a Lachat flow injection analyzer at the USDA Laboratory in Bushland, Texas.

Soil (1200 g) was placed into each chamber, and fresh feces (400 g) were spread evenly over the top of the soil. Both the soil and feces layers were about 5 cm thick. The soil was Amarillo fine sandy loam (fine−loamy, mixed, thermic

Figure 1. Photograph of the ammonia emission apparatus consisting of Tupperware air emission chambers and acid traps connected to a vacuum pump.

Aridic Paleustalfs) obtained near the WTAMU research feedyard located 10 km east of Canyon, Texas. Fresh feces were collected from the feedyard pen surface at the WTAMU research feedyard and frozen prior to use in the experiment. The feces were thawed at room temperature (21°C) one day before being placed into the chambers.

To simulate feedyard conditions, 23 mL of synthetic urine was added to each chamber every two days (equal to 6 L of daily excretion over a 14 m^2 area). Synthetic urine was prepared fresh before each application. The synthetic urine preparation was adapted from Shand et al. (2000) and prepared as follows: urea (21.4 g) was dissolved in 500 mL of water, and $KHCO_3$ (23.1 g), KCl (3.8 g), and K_2SO_4 (1.9 g) were dissolved together in another 500 mL of water. The two solutions (1 L total) were mixed immediately before application to avoid potential nitrogen losses or transformations in storage. In the treatments with simulated rainfall, an additional 173 mL (0.6 cm) of water was sprinkled over the manure surface at four−day frequencies. Rainfall was applied at the same time that synthetic urine was applied. The chambers were maintained at 21°C throughout the experiment.

The NBPT, which was obtained in 100% pure white crystalline form directly from the manufacturer, was dissolved in a small amount of water and sprayed on the manure surface at the rates and frequencies described above. Because a small amount of water was added to the manure whenever NBPT was sprayed on the surface, an equal amount of water was added to all treatments to avoid differences in manure moisture contents between those treatments that received different amounts of NBPT. The synthetic urine, NBPT solution, and water were all added by applying a misting spray equally across the manure surface after removing the top of the chamber. The chamber was left open for less than 2 min, which would affect the ammonia emissions less than 0.1% in a 24 h period.

The 8−day application frequency treatments (treatments 3, 4, 9, and 10) were terminated on day 16 after two full application periods. The 16−day and 32−day application frequency treatments were terminated on day 38, which allowed for two full application periods plus six days for the 16−day treatments, and one full application period plus six days for the 32−day treatments. All calculations were performed using two full application periods, except for the

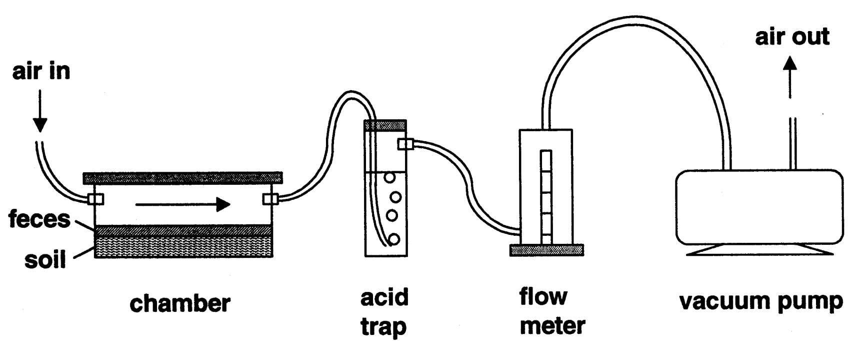

Figure 2. Schematic of the ammonia emission apparatus.

32−day treatments. The data obtained from day 32 to day 38 were used only for observation and were not used in calculation of mean NH_3 emission rates.

Mean NH_3 emission rates for each treatment were compared to test the effects of different application rates and frequencies. Statistical analyses were performed using Tukey's honestly significant difference (HSD) comparisons within the SPSS version 7.0 software package. Tukey's test controls the family−wise error rate rather than the individual error rate (Berthouex and Brown, 1994).

ECONOMIC ANALYSIS

Costs associated in applying NBPT for each treatment were calculated. NBPT costs were based on the cost of Agrotain, a commercially available liquid product with 20% active ingredient (NBPT), at a cost of \$11.90 L^{-1}. The NH_3 emissions of the treatment were compared with the control to obtain the reduction in emission for each treatment. Only benefits that had a direct monetary value, i.e., the increase in fertilizer value of the manure, were used in calculating the benefits. Other environmental air quality benefits may have a monetary value; however, the assignment of monetary values to these benefits is complicated and difficult and varies with the situation. Therefore, these other environmental benefits were not included in the economic analysis. Manure nitrogen was not measured at the completion of the experiment. For the economic analysis, we assumed that reduction in NH_3−N emissions would result in equal saving in manure N, and that no denitrification losses occurred. A fertilizer value of \$0.32 per kg of N was adapted from the studies of Parker et al. (1997). Benefits associated with each treatment were calculated from the price of N saved in the manure. The benefit/cost (B/C) analysis was performed based on the surface area in which the NBPT was applied, assuming a stocking density of 14 m^2 per animal.

RESULTS AND DISCUSSION

The emission rates for the 8−day frequency applications were less than all other application frequencies (table 2). None of the 16−day or 32−day applications were significantly different from the control. None of the simulated rainfall treatments were statistically different from their respective non−rainfall treatment. The 1 and 2 kg ha^{-1} treatments were not statistically different at any of the frequency application periods.

Although the average emission rates in table 2 suggest that NBPT applied every eight days will decrease NH_3 emissions, the graph of NH_3 emissions with time for the non−rainfall treatments shows that the 1 kg ha^{-1} treatment was not different from the control after the first eight days (day 9 to 16 mean = 1320 μg m^{-2} min^{-1} for control and 1190 μg m^{-2} min^{-1} for 1 kg ha^{-1}, $p = 0.38$, t−test) and was greater than the control on day 16 (fig. 3). The 2 kg ha^{-1} non−rainfall treatment decreased noticeably when NBPT was reapplied on day 8, yet, like the 1 kg ha^{-1} treatment, the emissions were slightly greater than the control on day 16 (fig. 3). These results suggest that more NBPT may be needed on day 16 than on day 8, as urea is accumulated on the simulated feedyard surface with time.

With the exception of the 8−day frequency application treatments, after day 8, the other non−rainfall treatments had NH_3 emissions statistically equal to or greater than the control, as verified by a statistical comparison of means using Tukey's test on day 9−16 emission rates. This indicates that NH_3 emissions may be suppressed for a short time, but if NBPT is not frequently applied, the buildup of urea could eventually result in a higher NH_3 emission rate than would have occurred had no NBPT been applied.

When NBPT was added on day 16 and day 32, there was little effect on NH_3 emissions for the non−rainfall treatments (fig. 3). However, for the rainfall treatments, the 2 kg ha^{-1} applications exhibited a drop in NH_3 emissions for a few days after the day 16 application. Because NBPT prevents urea from converting to NH_3, it is logical that the application of NBPT causes a buildup of urea in the manure. If this is true, then it is also possible that more NBPT will be required with time, as NBPT has a finite life, after which it is no longer effective. Further research is warranted to study this phe−

Table 2. Mean NH_3−N emission rates (μg m^{-2} min^{-1}) for three NBPT application rates, three application frequencies, and with or without simulated rainfall. Each mean is calculated from three replications.

NBPT Application								
Rate (kg ha^{-1})	Frequency (days)	Simulated Rainfall[a]	Mean[b] (μg m^{-2} min^{-1})	Std. Dev.	*n*	Minimum	Maximum	% of Control
0[c]	na	no	6 a	0.4	3	5	6	0.4
0[d]	na	no	1570 d	220	3	1430	1820	100
1	8	no	790 bc	80	3	710	880	51
1	8	yes	590 b	70	3	520	650	38
1	16	no	1510 d	2105	3	1300	1720	97
1	16	yes	1330 d	140	3	1220	1480	85
1	32	no	1590 d	250	3	1300	1770	101
1	32	yes	1570 d	2500	3	1290	1760	100
2	8	no	530 b	20	3	510	550	34
2	8	yes	490 ab	90	3	420	600	31
2	16	no	1540 d	1700	3	1400	1730	99
2	16	yes	1230 cd	1902	3	1020	1370	78
2	32	no	1400 d	160	3	1240	1570	89
2	32	yes	1190 cd	1701	3	1070	1390	76

[a] Treatments with simulated rainfall received 0.6 cm water added every four days.
[b] Means with different letters are significantly different using Tukey's HSD test ($\alpha = 0.05$).
[c] Blank (no soil/manure).
[d] Control (soil/manure only).

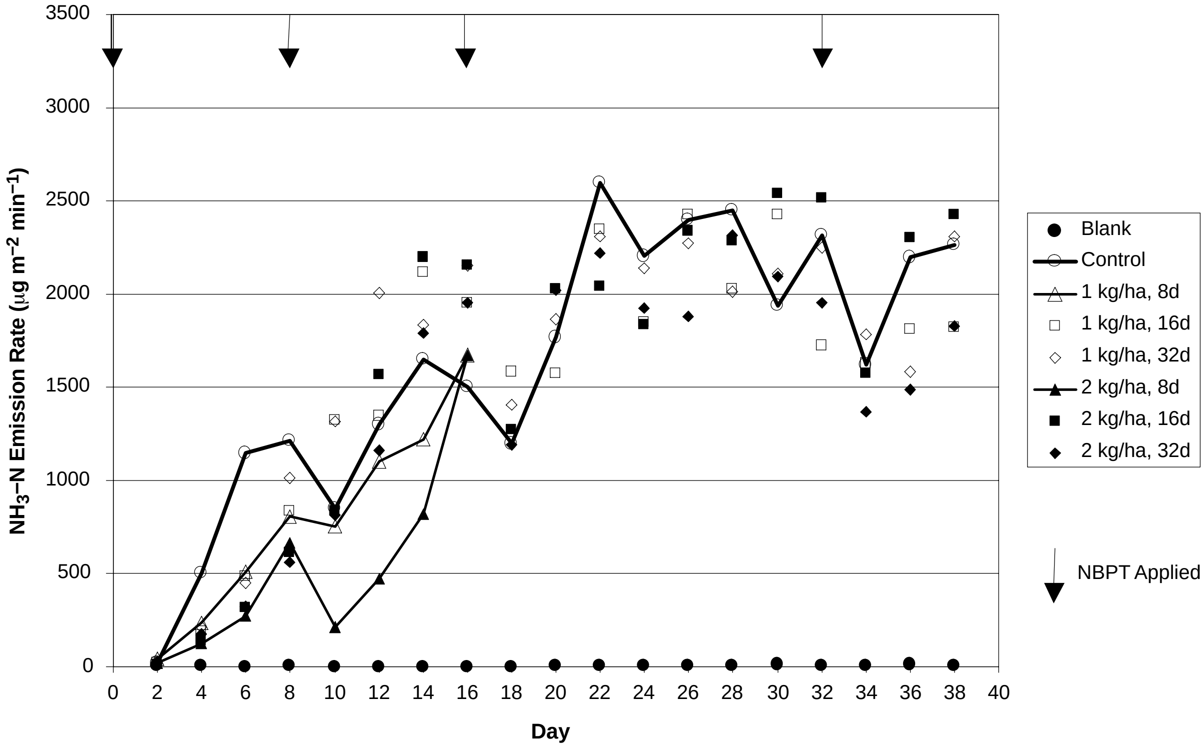

Figure 3. Variation of average daily NH_3−N emission rates over the 38−day study period in the treatments without simulated rainfall. Each data point is the mean of three replications.

nomenon and determine the fate of urea in the feedyard surface and optimum NBPT application rate for feedyard conditions.

The application of water every four days did not result in statistically different NH_3−N emissions (table 2), although there was some evidence that water played a role in the effectiveness of the NBPT (fig. 4). It is possible that the water helped spread the NBPT vertically through the manure surface, thereby increasing its effectiveness.

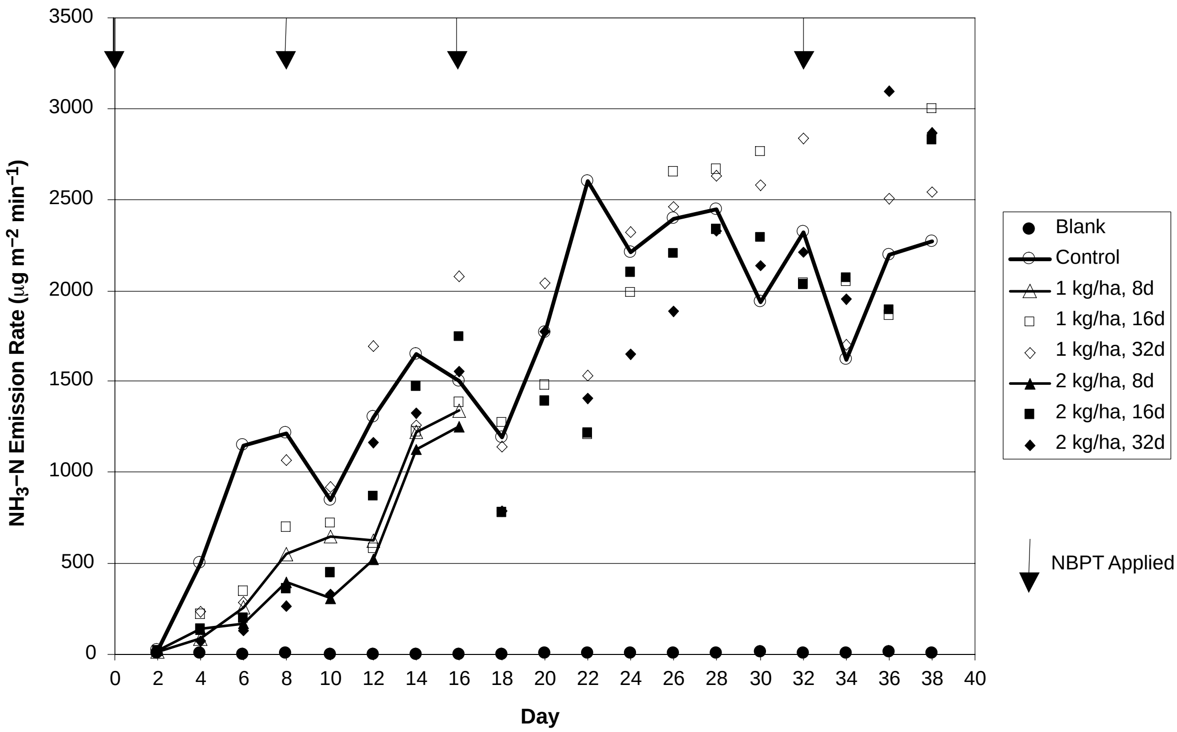

Figure 4. Variation of average daily NH_3−N emission rates over the 38−day study period in the treatments with simulated rainfall. Each data point is the mean of three replications.

The mean daily emission rates of the present study were about half of the emission rates reported by Shi et al. (2001). In similar previous studies, fresh feces and urine were added at the onset of the experiment, and no additional urine or manure was added during the experiment (Shi et al., 2001). In Shi's research, emissions were highest initially and decreased rapidly with time. In the present experiment, the addition of synthetic urine every two days resulted in a continuous increase in emission rates until about day 20. This difference in experimental design is likely the cause of the differing NH_3 emissions between Shi's experiment and this one.

The NBPT was mixed into the manure in Shi's experiments, whereas the urease inhibitor was sprayed over the manure surface in this experiment. In practical conditions, incorporation requires additional labor, and it is probable that cattle hoof action would be adequate for mixing the NBPT into the manure. Spraying also requires additional labor; however, it might be possible for NBPT to be applied through sprinklers already in place to minimize dust emissions in some feedyards.

Cole (1999) reported that a feedyard containing 50,000 head could release about 4500 kg of NH_3 nitrogen per day, which is based on the assumption that 50% of the nitrogen fed would be lost as ammonia gas. Based on the NH_3 emission rate of the control in this experiment, and assuming 14 m^2 pen space per animal, an estimated 1580 kg of NH_3 nitrogen would be released per day, or 35% of Cole's estimate.

The application of 6 L of synthetic urine per day per 14 m^2 animal space corresponds to a daily nitrogen loading of 4.3 g N m^{-2} d^{-1}. For the control, the mean NH_3−N emission rate of 1,570 μg m^{-2} min^{-1} corresponds to 2.3 g N m^{-2} d^{-1}. Thus, 53% of the daily nitrogen load was captured as volatilized NH_3−N.

The mean NH_3 emission rate for the control in this experiment was 1570 μg m^{-2} min^{-1}, which compares to 3307 μg m^{-2} min^{-1}, as reported in the 21−day laboratory study of Shi et al. (2001). Koziel et al. (2004) reported NH_3 emissions measured in field studies in West Texas of 289, 1816, and 1666 μg m^{-2} min^{-1} for winter, spring, and summer seasons, respectively. Koziel used a 26.5 cm diameter dynamic flow−through flux chamber, which was placed on the manure surface at a commercial feedyard. Clean air was introduced into the flux chamber at a flow rate of 6.5 L min^{-1}, and NH_3 concentrations were measured using a TEI 17C chemiluminescence continuous analyzer. Koziel's flow rate per unit area was 117 L min^{-1} m^{-2}, compared to 50 L min^{-1} m^{-2} in the present study and 80 L min^{-1} m^{-2} in Shi's research. In the present study, the mean emission rates in the control are similar to those reported by Koziel et al. (2004) for spring and summer feedyard conditions.

Economics

The benefits derived from the urease inhibitor such as decrease in emissions and increase in fertilizer value must be sufficient to justify the cost of the amendment. Because only the 8−day application frequencies had significantly lower NH_3 emissions, the benefit/cost analysis was performed on these four treatments. The economic analysis using area−based extrapolation indicated a B/C ratio of 0.48 to 0.60 for the 1 kg ha^{-1} treatments, as compared to 0.32 to 0.33 for the 2 kg ha^{-1} treatments. NH_3 emissions were lower in the 2 kg ha^{-1} treatment, although the B/C ratio was lower. With the highest B/C of 0.60, the analysis indicates that application of NBPT is not economical at 1 kg ha^{-1} and an 8−day application frequency, based solely on the decreased NH_3−N loss from the manure (table 3). However, other air quality and environmental benefits may make NBPT a more viable option in the future.

Conclusions

The following conclusions were drawn from this laboratory research project:

- When applied every eight days and without simulated rainfall, NH_3 emissions were reduced by 49.4% and 66.0% at NBPT application rates of 1 and 2 kg ha^{-1}, respectively.
- NBPT must be applied at a frequency less than 16 days in order to be effective at reducing NH_3 emissions. Application at 16 or 32 day frequencies was not significantly different from the control.
- Simulated rainfall reduced the NH_3 emission rates from 1% to 25% as compared to the non−rainfall treatments, although the differences were not statistically different.
- The use of NBPT for reducing NH_3 emissions from beef cattle feedyards continues to look promising based on the results of this and other laboratory studies. However, the possible buildup of urea could require higher NBPT application rates with time. Additional research is warranted to evaluate the performance of the urease inhibitor in actual field conditions.

Table 3. Economics of using NBPT at the rates shown. Benefits equal the additional nitrogen value in the manure, while costs equal the NBPT cost only, with no application costs included.

	1 kg ha^{-1} NBPT Applied at 8−Day Frequency		2 kg ha^{-1} NBPT Applied at 8−Day Frequency	
	No Rainfall	With Rainfall	No Rainfall	With Rainfall
Decrease in NH_3−N emissions (kg animal $unit^{-1}$ $year^{-1}$)	5.7	7.2	7.6	7.9
Increase in fertilizer value of manure ($ animal $unit^{-1}$ $year^{-1}$)	1.82	2.30	2.43	2.52
Cost of NBPT ($ animal $unit^{-1}$ $year^{-1}$)	3.80	3.80	7.60	7.60
Benefit/cost ratio	0.48	0.60	0.32	0.33

Note: One animal unit = 454 kg beef animal; stocking density = 14 m^2 per animal.

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